A SYSTEM AND METHOD FOR REPLICATING VOLUME HOLOGRAMS

BACKGROUND OF THE INVENTION

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Field of the Invention

The invention pertains to the use of contact holography to form multiple holograms and, more particularly, to the use of contact holography and a master

10 hologram to make replica gratings, lenses, switches and other images wherein one or both of the master hologram and corresponding replica comprise a polymer-dispersed liquid crystal (PDLC) material.

Description of the Related Art

15 Once a hologram has been recorded, whether using simple or complex optical geometries, it is often desired to reproduce or reconstruct the hologram so as to have multiple copies which are substantially identical to the originally recorded hologram. There are numerous methods for reconstructing holograms, however these are cumbersome and involve retracing the steps used to create the original or master

20 hologram. Unfortunately, where complex geometries are involved, this is neither an efficient nor a practical method for performing mass reconstruction.

By way of example, U.S. Patent No. 3,580,655 to Leith ("Leith") which is incorporated herein by reference, sets forth multiple methods both for formation of the master hologram and for reconstruction of the master hologram, either for viewing or for

25 permanent recording. While the subject matter of the current invention is not centered on the formation of the master hologram, the advantages of the current invention are readily apparent when the complexity of this initial formation is recognized. For example, **FIG. 1** (Fig. 7 of Leith) illustrates one of the simplest geometries for forming a master hologram. This simple configuration illustrates the basic components for simple

30 holographic construction, including a coherent light source **10** emitting an incident beam **12**. From this incident beam **12**, two separate beams are formed. A prism **14** or similar light-splitting or directing device intercepts part of the incident beam **12** and directs a reference beam **16** to a detector plate **18**. Simultaneously, a part of the incident beam is

diffused by a diffusion screen **20** and diffracts off an object **22**, forming an object beam **24**, which also passes onto the detector plate **18**. The interaction between the reference beam **16** and the object beam **24** produces an off-axis hologram, in the form of multiple Fresnel patterns and interference fringes.

5   Further in Leith, there is a method and system for using the master hologram from **FIG. 1** to produce replicas of the master hologram. **FIG. 2a** represents the simplest system and method for duplicating the master hologram. Referring to prior art **FIG. 2a**, there is an incident beam **12** from a coherent light source **10** which forms two separate beams, a reference beam **16** and an object beam **24**. In this case, object beam **24** results

10   from the interaction of part of incident beam **12** with the master hologram **26**. Due to the grating effect of the master hologram **26**, the object beam is directed along the formation angle and a detector **18** is placed at the intersection of the reference beam **16** and the object beam **24**, forming a replica of the interference pattern comprising master hologram **26**. In this case, the object beam forms a virtual image of master hologram **26** which is

15   recorded on the detector **18**. The real image is not used in the reproduction process.

As is clear to one skilled in the art, this method of master hologram duplication, while viable, results in a number of disadvantages. In any situation involving light traveling through an optical train, there is the potential for misalignment of the optical elements. Further there are inherent efficiency limits for each optical element. These

20   disadvantages can result in unwanted diffraction, reflection, and in some cases aberration of the beams. Additionally, while lasers have improved coherence parameters, coherence length remains an issue. Even the simplest dual beam recording and duplication systems described above require precise alignment for optimal results. The conventional systems above also require multiple optical elements even for the simplest holographic formation

25   geometries. Consequently, complex geometry hologram formation is not available with the Leith system because of the length and requisite multiple components of the optical train.

The prior art also contemplates a single beam master hologram duplication system that greatly reduces the number of necessary optical components. Referred to as contact

30   printing, this system for duplicating a master hologram resembles in many respects the art of photography. The master hologram and a holographic detection plate (e.g., emulsion plate) are placed in optical contact with one another and exposed to light. Photographic

development of the holographic detection plate results in a replica master hologram. For a fully successful reproduction, the optical contact between the master hologram and the holographic detection plate must be such that there is no loss of resolution within the interference fringes. Establishing the requisite optical contact has proved to be a

5   significant limiting factor in attempts to use contact printing for duplication of holograms. Consequently, the prior art single-beam contact printing method, though it reduces the number of optical elements necessary for duplication of a master hologram, poses new optical hurdles to the art of hologram replication.

Referring to **FIG. 2b**, a prior art single beam contact printing system is illustrated

10   in accordance with U.S. Patent No. 5,547,786 to Brandstetter, et al. ("Brandstetter"), the specification of which is incorporated herein by reference. The system of Brandstetter includes a source of monochromatic, collimated light of substantially fixed wavelength such as laser **10** which produces an output beam **12**, referred to as the replication or recording beam, and directs that beam through beam conditioning means **80**, which

15   preferably comprises lenses **82** and **84**, pinhole **86**, and filter **88**. Lenses **82** and **84** and pinhole **86** are provided to collimate beam **12** and to expand that beam to the desired size filter **88** is provided to control or adjust the intensity or amplitude of beam **12** across its profile as desired. Subsequent to conditioning by means **80**, the conditioned beam **12** is directed at a desired angle onto master holographic optical element **26**, passes through,

20   and directly enters a phase recording medium **18**, such as a photopolymer layer that has been applied onto the backside of the master holographic optical element.

The method for forming the replica within the photopolymer layer requires a polymerization step which is separate from the recording step. Further, the resulting replica hologram is not switchable. Further, the recording mediums currently available as

25   blanks for hologram duplication are limited in their ability to provide optimal optical contact with the master hologram.

Accordingly, there remains a need for a system and method for mass reproduction of holograms, having a single beam contact printing method using an optically superior recording medium.

30   In conventional contact holography methods and systems, situations exist wherein the use of a static, as opposed to a switchable, master hologram is limiting. First, a static hologram is limited to a single diffraction efficiency, which is always ON (i.e., it cannot

be turned OFF). Second, even though a non-recording wavelength theoretically should pass through the static hologram without causing recording in the blank, in practice this is not the case. Instead, a non-recording, incoherent wavelength passing through a static master may result in unwanted scattering and cross-coupling of phase information which can decrease diffraction efficiency, introduce cross-gratings, increase haze, and generally decrease the signal-to-noise properties of the replicated grating. These limitations of the static master hologram result in difficulties with contact recording schemes that require either *in situ* pre-recording or post-recording irradiation of the blank.

Accordingly, a need remains for a non-static master hologram for use in a contact printing method and system.

BRIEF SUMMARY OF THE INVENTION

The present invention offers increased efficiency and quality in the duplication of a master hologram utilizing an improved method and system of contact printing. A first embodiment of an improved method and system of contact printing employs a polymer-dispersed liquid crystal (PDLC) recording medium as the duplication blank. The optical qualities of the PDLC material described herein provide an improved method of duplication using single beam contact printing regardless of the material comprising the master hologram. Thus, master holograms originally recorded using highly complex optical geometries (e.g., computer generated holograms) are capable of duplication without the need for multiple beam power/intensity balancing and long recording times. The improved hologram contact printing method and system described herein works with virtually any type of master hologram, including both reflection and transmission holograms.

A first embodiment of the present invention describes a system for duplicating a hologram which includes a radiation source for emitting a coherent beam of radiation, a hologram, and a recording substrate comprised of a polymer-dispersed liquid crystal material for recording a replica of the hologram therein. The components of the system are arranged such that the hologram and the recording substrate are in optical contact with one another and they are placed in a path of the coherent beam of radiation.

4

A second embodiment of the present invention describes a method for duplicating a hologram which includes the following steps of (1) directing a coherent incident radiation beam at a first optical component; (2) transmitting the coherent incident radiation beam through the first optical component forming a transmitted beam, to a

5   second optical component having a hologram recorded therein; and (3) diffracting the transmitted beam via the hologram forming a diffracted radiation beam. The incident beam and the diffracted beam interfere within the first optical component to form a replica of the hologram therein.

A third embodiment of the present invention describes a method for contact

10   recording at least one hologram which includes the following steps of: (1) directing a coherent radiation beam at a first optical component having a hologram recorded therein and (2) diffracting a first portion and transmitting a second portion of the coherent radiation beam through the first optical component to a second optical component. The transmitted beam and the diffracted beam interfere within the second optical component

15   to form a replica of the hologram therein.

A fourth embodiment of the present invention describes a method for contact recording at least one hologram which includes the following steps of: (1) optically contacting at least one master hologram to at least one holographic blank to form a master/blank assembly; (2) exposing the master/blank assembly to a pre-recording beam;

20   (3) exposing the master/blank assembly to a recording beam; and (4) exposing the master/blank assembly to a post-recording beam, wherein the master/blank assembly remains optically contacted throughout each exposure.

A fifth embodiment of the present invention describes a method for contact recording at least one hologram which includes the following steps: (1) optically

25   contacting at least one master hologram to at least one holographic blank to form a master/blank assembly; (2) exposing the master/blank assembly to a recording beam; and (3) exposing the master/blank assembly to a post-recording beam, wherein the master/blank assembly remains optically contacted throughout each exposure.

A sixth embodiment of the present invention describes a system for contact

30   recording at least one hologram which includes at least one master hologram, at least one holographic blank, a pre-recording beam, and a recording beam, wherein the at

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least one master hologram and the at least one holographic blank are in optical contact during exposure to the pre-recording beam and the recording beam.

A seventh embodiment of the present invention describes a system for contact recording at least one hologram which includes at least one master hologram, at least one holographic blank, a recording beam, and a post-recording beam, wherein the at least one master hologram and the at least one holographic blank are in optical contact during exposure to the recording beam and the post-recording beam.

An eighth embodiment of the present invention describes a system for contact recording at least one hologram which includes at least one master hologram, at least one holographic blank, a pre-recording beam, a recording beam, and a post-recording beam, wherein the at least one master hologram and the at least one holographic blank are in optical contact during exposure to the pre-recording beam, the recording beam, and the post-recording beam.

BRIEF DESCRIPTION OF THE FIGURES

In the drawings:

FIG. 1 is a schematic view of a conventional system for forming a master transmission hologram;

FIG. 2a is a schematic view of a conventional system for forming a replica of the master hologram of **FIG. 1**;

FIG. 2b is a schematic view of a conventional system for forming a replica hologram via a contact printing method;

FIG. 3 is a schematic view of a system according to an embodiment of the present invention for forming a replica hologram in a PDLC blank from a master transmission hologram;

FIG. 4 is a schematic view of a system according to an embodiment of the present invention for forming a replica hologram in a PDLC blank from a master reflection hologram;

5   **FIG. 5** is a schematic view of a PDLC blank according to an embodiment of the present invention for forming a replica hologram therein;

FIG. 6 is a schematic view of a recording system for forming a transmission hologram according to the present invention;

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FIGS. 7a and **7b** are elevational views of a reflection grating in accordance with the present invention having planes of polymer channels and liquid crystal channels disposed parallel to the front surface, in the absence of a field (**FIG. 7a**) and with an electric field applied (**FIG. 7b**), wherein the liquid crystal utilized in the formation of the grating has a

15   positive dielectric anisotropy;

FIG. 8a and **8b** are elevational views of a reflection grating in accordance with the invention having planes of polymer channels and liquid crystal channels disposed parallel to the front surface of the grating, in the absence of an electric field (**FIG. 8a**) and with

20   an electric field applied (**FIG. 8b**), wherein the liquid crystal utilized in the formation of the grating has a negative dielectric anisotropy;

FIG. 9a, 9b, 9c, 9d, 9e, and 9f are pre-recording, exposure, and post-recording views of a contact printing system incorporating a switchable H-PDLC master according to an

25   embodiment of the present invention;

FIG. 10a and **10b** are reflection and transmission exposure views wherein a switchable H-PDLC master is partially switched according to an embodiment of the present invention;

30

7

FIG(s). 11(a)-(b) are multiple beam, multiple master, multiple blank exposure views utilizing a reflective and transmissive switchable H-PDLC master, according to embodiments of the present invention;

5   **FIG(s). 12(a)-(b)** are multiple beam, multiple master, multiple blank exposure views utilizing reflective and transmissive switchable H-PDLC masters respectively, to form an RGB stacked replica, according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

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Referring to **FIGS. 3** and **4**, the improved contact printing method and systems described herein comprise the following basic components: a coherent light source **31** emitting an incident beam **33**, a master hologram **35** emitting diffracted beam **34** and transmitted beam **36**, a polymer-dispersed liquid crystal ("PDLC") blank **37** for recording

15   a replica of the master hologram, and, optionally, an absorption filter **39**. As discussed further, the order and placement of these elements with respect to one another vary depending on whether the master hologram is transmissive or reflective.

The PDLC materials described herein may be used in both the PDLC blank **37** and the master hologram **35**. However, neither the master hologram **35** nor the blank **37**

20   are limited to this PDLC material. The master hologram **35** may be formed on a conventional photographic plate or similar emulsion-type recording medium, or by computer generation, for example. Similarly, the blank **37** may be formed of an appropriate photosensitive material as determined by one skilled in the art.

In accordance with an embodiment of the present invention there is provided a

25   blank recording or master hologram medium comprised of a PDLC material comprising a monomer, a liquid crystal material, a cross-linking monomer, a coinitiator and a photoinitiator dye. These PDLC materials exhibit clear and orderly separation of the liquid crystal and cured polymer, whereby the PDLC material advantageously provides high quality holographic gratings. The PDLC materials of the present invention are also

30   advantageously formed in a single step. The present invention also utilizes a unique photopolymerizable prepolymer material that permits in situ control of significant characteristics of the resulting gratings, such as domain size, shape, density, ordering, and

8

the like. Furthermore, the methods and materials of the present invention can be used to prepare PDLC materials that function as switchable transmission or reflection holograms or holographic gratings.

Polymer-dispersed liquid crystal materials, methods, and devices contemplated for use in the practice of the present invention are also described in R. L. Sutherland et al., "Bragg Gratings in an Acrylate Polymer Consisting of Periodic Polymer-Dispersed Liquid-Crystal Planes," Chemistry of Materials, No. 5, pp. 1533-1538 (1993) ("Chemistry of Materials"); R. L. Sutherland, et al., "Electrically Switchable Volume Gratings in Polymer-Dispersed Liquid Crystals," Applied Physics Letters, Vol. 64, No. 9, pp. 1074-1076 (1984); and T. J. Bunning, et al., "The Morphology and Performance of Holographic Transmission Gratings Recorded in Polymer-Dispersed Liquid Crystals," Polymer, Vol. 36, No. 14, pp. 2699-2708 (1995), all of which are fully incorporated by reference into this specification.

The PDLC material employed in the practice of the present invention creates a switchable hologram in a single step. A new feature of a preferred PDLC material is that illumination by an inhomogeneous, coherent light pattern initiates a patterned, anisotropic diffusion (or counter-diffusion) of polymerizable monomer and second phase material, particularly liquid crystal. Thus, alternating well-defined channels of second phase-rich material, separated by well-defined channels of nearly pure polymer, are produced in a single-step process.

A resulting preferred PDLC material has an anisotropic spatial distribution of phase-separated liquid crystal droplets within the photochemically cured polymer matrix. Conventional PDLC materials made by a single-step process can achieve at best only regions of larger liquid crystal droplets and smaller liquid crystal droplets in a polymer matrix. The large bubble sizes are highly scattering, producing a hazy appearance and multiple order diffractions, in contrast to the well-defined first order diffraction and zero order diffraction resulting from the small liquid crystal droplets of the preferred PDLC material in well-defined channels of liquid crystal-rich material. Reasonably well-defined alternately liquid crystal-rich channels and nearly pure polymer channels in a PDLC material are possible by multi-step processes, but such processes do not achieve the precise control of morphology over liquid crystal droplet size and distribution of size and width of the polymer and liquid crystal-rich channels made possible by a preferred

PDLC material.

The features of the PDLC material are influenced by the components used in the preparation of the homogeneous starting mixture and, to a lesser extent, by the intensity of the incident light pattern. In a preferred embodiment, the prepolymer material

5   comprises a mixture of a photopolymerizable monomer, a second phase material, a photoinitiator dye, a coinitiator, a chain extender (or cross-linker), and, optionally, a surfactant.

In a preferred embodiment, the two major components of the prepolymer mixture are the polymerizable monomer and the second phase material, which are preferably

10   completely miscible. Highly functionalized monomers are preferred because they form densely cross-linked networks which shrink to some extent and tend to squeeze out the second phase material. As a result, the second phase material is moved anisotropically out of the polymer region and, thereby, separated into well-defined, polymer-poor, second phase-rich regions or domains. Highly functionalized monomers are also

15   preferred because the extensive cross-linking associated with such monomers yields fast kinetics, allowing the hologram to form relatively quickly, whereby the second phase material will exist in domains of less than approximately 0.1 μm.

Highly functionalized monomers, however, are relatively viscous. As a result, these monomers do not tend to mix well with other materials, and they are difficult to

20   spread into thin films. Accordingly, it is preferable to utilize a mixture of pentaacrylates in combination with di-, tri-, and/or tetra-acrylates in order to optimize both the functionality and viscosity of the prepolymer material. Suitable acrylates, such as triethyleneglycol diacrylate, trimethylolpropane triacrylate, pentaerythritol triacrylate, pentaerythritol tetraacrylate, pentaerythritol pentaacrylate, and the like can be used in the

25   present invention. In a preferred embodiment, it has been found that an approximately 1:4 mixture of tri- to penta-acrylate facilitates homogeneous mixing, while providing a favorable mixture for forming 1-100 μm thin films on the optical plates.

The second phase material of choice for use in the practice of the present invention is a liquid crystal. This also allows an electro-optical response in the resulting

30   hologram. The concentration of liquid crystal employed should be large enough to allow a significant phase separation to occur in the cured sample, but not so large as to make the sample opaque or very hazy. Below about 20% by weight very little phase separation

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occurs and diffraction efficiencies are low. Above about 35% by weight, the sample becomes highly scattering, reducing both diffraction efficiency and transmission. Samples fabricated with approximately 25% by weight of liquid crystal typically yield good diffraction efficiency and optical clarity. In prepolymer mixtures utilizing a

5   surfactant, the concentration of liquid crystal may be increased to 35% by weight without loss in optical performance by adjusting the quantity of surfactant. Suitable liquid crystals contemplated for use in the practice of the present invention include the mixture of cyanobiphenyls marketed as E7 by Merck, 4'-n-pentyl-4-cyanobiphenyl, 4'-n-heptyl-4-cyanobiphenyl, 4'-octaoxy-4-cyanobiphenyl, 4'-pentyl-4-cyanoterphenyl,4-

10   methoxybenzylidene-4'-butylaniline, and the like. Other second phase components are also possible.

By way of example, a polymer-dispersed liquid crystal material employed in the practice of the present invention is formed from a prepolymer material that is a homogeneous mixture of a polymerizable monomer comprising dipentaerythritol

15   hydroxypentaacrylate (available, for example, from Polysciences, Inc., Warrington, Pa.), approximately 10-40% by weight of the liquid crystal E7 (which is a mixture of cyanobiphenyls marketed as E7 by Merck and also available from BDH Chemicals, Ltd., London, England), the chain-extending monomer N-vinylpryrrolidone("NVP") (available from the Aldrich Chemical Company, Milwaukee, Wis.), coinitiator N-phenylgylycine

20   ("NPG") (also available from the Aldrich Chemical Company, Milwaukee, Wis.), and the photoinitiator dye rose bengal ester; (2,4,5,7-tetraiodo-3',4',5',6'-tetrachlorofluroescein-6-acetate ester) marketed as RBAX by Spectragraph, Ltd., Maumee, Ohio). Rose bengal is also available as rose bengal sodium salt (which must be esterfied for solubility) from the Aldrich Chemical Company. This system has a very fast curing speed which results in

25   the formation of small liquid crystal micro-droplets.

A preferred example of a PDLC duplication blank 38 is illustrated in **FIG. 5**. This cross-sectional view of a duplication blank 38 is formed of a layer 50 of the PDLC material sandwiched between a pair of indium-tin-oxide ("ITO") coated glass slides 52a and 52b and spacers 54.

30   In an exemplary embodiment, the master hologram 35, as shown in **FIG. 3** and **FIG. 4**, is formed from PDLC material. In this embodiment, the interior of master hologram 35 reveals a Bragg transmission grating 56 (**FIG. 6**) formed when PDLC

11

material layer **50** is exposed to an interference pattern from two intersecting beams of coherent laser light. In **FIG. 6**, there is shown an exemplary system for recording a master transmission hologram using PDLC materials of the present invention. A coherent light source **62** (e.g., Ar ion laser) is incident upon a spatial filter **64** and a

5   collimating lens **66** prior to being divided via a dual slit aperture **68** and impinging upon a prism **70** causing the dual beams to interfere within the layer of PDLC material **50**. Further within this set-up, similar to **FIG. 5**, the PDLC material is sandwiched between layers of ITO glass slides **52a** and **52b**, separated by spacers **54**. Also, in order to insure optical homogeneity, neutral density filters **57** are placed before slide **52a** and after slide

10   **52b**, separated by an index matching fluid **53**. Finally, in order to allow control of the liquid crystal orientation within the PDLC material, both during and after formation of the hologram, so as to ascertain desired Bragg grating angles, electrodes **55** are provided in electrical contact with the ITO glass slides **52a** and **52b**. Similarly, one skilled in the art will appreciate the variations and additions of reflective material necessary to form a

15   Bragg reflection grating as opposed to a Bragg transmission grating.

The PDLC material is a mixture of liquid crystal and prepolymer material homogenized to form a viscous solution by suitable means (e.g., ultrasonification) and spread between, for example, ITO coated glass slides with spacers of nominally 1-100 μm thickness and, preferably, 4-20 μm thickness. The ITO is electrically conductive and

20   serves as an optically transparent electrode. Preparation, mixing and transfer of the prepolymer material onto the glass slides are preferably performed in conditions outside of the absorbance spectrum of the selected photoinitiator dye.

The sensitivity of the prepolymer materials to light is dependent on the photoinitiator dye and its concentration. Higher dye concentration leads to higher

25   sensitivity. In most cases, however, the solubility of the photoinitiator dye limits the concentration of the dye and, thus, the sensitivity of the prepolymer material. Nevertheless, it has been found that for most general applications photoinitiator dye concentrations in the range of 0.2-0.4% by weight are sufficient to achieve desirable sensitivities and allow for a complete bleaching of the dye in the recording process,

30   resulting in colorless final samples. Photoinitiator dyes that are useful in generating PDLC materials in accordance with the present invention are rose bengal ester (2,4,5,7-tetraiodo-3',4',5',6'-tetrachlorofluroescein-6-acetate ester); rose bengal sodium salt; eosin;

12

eosin sodium salt; 4,5-diiodosuccinyl fluorescein; camphorquinone; methylene blue; and the like. These dyes allow a sensitivity to recording wavelengths across the visible spectrum from nominally 400 nm to 700 nm. Suitable near-infrared dyes, such as cationic cyanine dyes with trialkylborate anions having absorption from 600-900 nm, as well as

5 merocyanine dyes derived from spiropyran, should also find utility in connection with the present invention.

The coinitiator employed in the practice of the present invention controls the rate of curing in the free radical polymerization reaction of the prepolymer material. Optimum phase separation and, thus, optimum diffraction efficiency in the resulting PDLC material

10 are a function of curing rate. It has been found that favorable results can be achieved utilizing the coinitiator in the range of 2-3% by weight. Suitable coinitiators include N-phenylglycine; triethylene amine; triethanolamine; N,N-dimethyl-2,6-diisopropyl aniline; and the like.

Other suitable dyes and dye-coinitiator combinations that should be suitable for

15 use in the present invention, particularly for visible light, include eosin and triethanolamine; camphorquinone and N-phenyglycine; fluorescein and triethanolamine; methylene blue and triethanolamine or N-phenylglycine; erythrosin B and triethanolamine; indolinocarbocyanine and triphenyl borate; iodobenzospiropyran and triethylamine; and the like.

20 The chain extender (or cross-linker) employed in the practice of the present invention helps to increase the solubility of the components in the prepolymer material, as well as increase the speed of polymerization. The chain extender is preferably a smaller vinyl monomer as compared with the pentaacrylate, whereby it can react with the acrylate positions in the pentaacrylate monomer, which are not easily accessible to

25 neighboring pentaacrylate monomers as a result of steric hindrance. Thus, reaction of the chain extender monomer with the polymer increases the propagation length of the growing polymer and results in high molecular weights. It has been found that a chain extender in the range of 10-18% by weight maximizes the performance in terms of diffraction efficiency. In a preferred embodiment, it is expected that suitable chain

30 extenders can be selected from the following: N-vinyl pyrrolidone; N-vinyl pyridine; acrylonitrile; N-vinyl carbazole; and the like.

It has been found that the addition of a surfactant material, for example, octanoic

13

acid, in the prepolymer material lowers the switching voltage and improves the diffraction efficiency. In particular, the switching voltage for PDLC materials containing a surfactant are significantly lower than those of a PDLC material made without the surfactant. While not wishing to be bound by any particular theory, it is believed that

5   these results may be attributed to the weakening of the anchoring forces between the polymer and the phase-separated liquid crystal droplets. Scanning electron microscopy ("SEM") studies have shown that droplet sizes in PDLC materials including surfactants are reduced to the range of 30-50 nm and the distribution is more homogeneous. Random scattering in such materials is reduced due to the dominance of smaller droplets, thereby

10   increasing the diffraction efficiency. Thus, it is believed that the shape of the droplets becomes more spherical in the presence of surfactant, thereby contributing to the decrease in switching voltage.

For more general applications, it has been found that samples with as low as 5% by weight of surfactant exhibit a significant reduction in switching voltage. It has also

15   been found that, when optimizing for low switching voltages, the concentration of surfactant may vary up to about 10% by weight (dependent mostly on liquid crystal concentration) after which there is a large decrease in diffraction efficiency, as well as an increase in switching voltage (possibly due to a reduction in total phase separation of liquid crystal). Suitable surfactants include octanoic acid; heptanoic acid; hexanoic acid;

20   dodecanoic acid; decanoic acid; and the like.

In samples utilizing octanoic acid as the surfactant, it has been observed that the conductivity of the sample is high, presumably owing to the presence of the free carboxyl (COOH) group in the octanoic acid. As a result, the sample increases in temperature when a high frequency ($\sim$2 KHz) electrical field is applied for prolonged periods of time.

25   Thus, it is desirable to reduce the high conductivity introduced by the surfactant, without sacrificing the high diffraction efficiency and the low switching voltages. It has been found that suitable electrically switchable gratings can be formed from a polymerizable monomer, vinyl neononanoate ("VN") $C_8 H_{17} CO_2 CH=CH_2$, commercially available from the Aldrich Chemical Co. in Milwaukee, Wisconsin.

30   Favorable results have also been obtained where the chain extender NVP and the surfactant octanoic acid are replaced by 6.5% by weight VN. VN also acts as a chain extender due to the presence of the reactive acrylate monomer group. In these variations,

14

high optical quality samples were obtained with about 70% diffraction efficiency, and the resulting gratings could be electrically switched by an applied field of 6 V/μm.

PDLC materials in accordance with the present invention may also be formed using a liquid crystalline bifunctional acrylate as the monomer ("liquid crystal

5   monomer"). The liquid crystal monomers have an advantage over conventional acrylate monomers due to their high compatibility with the low molecular weight nematic liquid crystal materials, thereby facilitating formation of high concentrations of low molecular weight liquid crystal and yielding a sample with high optical quality. The presence of higher concentrations of low molecular weight liquid crystals in the PDLC material

10   greatly lowers the switching voltages (e.g., to ~2 V/μm). Another advantage of using liquid crystal monomers is that it is possible to apply low AC or DC fields while recording holograms to pre-align the host liquid crystal monomers and the low molecular weight liquid crystal so that a desired orientation and configuration of the nematic directors can be obtained in the liquid crystal droplets. The chemical formulae of several

15   suitable liquid crystal monomers are as follows:

I. $CH_2=CH-COO-(CH_2)_6O-C_6 H_5-C_6H_5-COO-CH=CH_2$

II. $CH_2 CH-(CH_2)_8-COO-C_6H_5-COO-(CH_2)_8-CH=CH_2$

III. $H(CF_2)_{10} CH_2O-CH_2-C(=CH_2)-COO-(CH_2CH_2O)_3CH_2CH_2O-COO-CH_2-$

20   $C(=CH_2)-CH_2O(CF_2)_{10} H$

Semifluorinated polymers are known to show weaker anchoring properties and also significantly reduced switching fields. Thus, it is believed that semifluorinated acrylate monomers, which are bifunctional and liquid crystalline will find suitable

25   application in the present invention.

In a preferred embodiment, the prepolymer material utilized to make a reflection grating comprises a monomer, a liquid crystal, a cross-linking monomer, a coinitiator, and a photoinitiator dye. In a preferred embodiment, the reflection grating is formed from prepolymer material comprising by total weight the monomer dipentaerythritol

30   hydroxypentaacrylate ("DPHPA"), 34% by total weight of a liquid crystal comprising a mixture of cyano biphenyls (known commercially as "E7"), 10% by total weight of a cross-linking monomer comprising NVP, 2.5% by weight of the coinitiator N-

15

phenylglycine ("NPG"), and 10^{-5} to 10^{-6} gram moles of a photoinitiator dye comprising rose bengal ester. Further, as with transmission gratings, the addition of surfactants is expected to facilitate the same advantageous properties discussed above in connection with transmission gratings. It is also expected that similar ranges and variation of

5   prepolymer starting materials will find ready application in the formation of suitable reflection gratings.

It has been determined by low voltage, high resolution scanning electron microscopy ("LVHRSEM") that the resulting material comprises a fine grating with a periodicity of 165 nm with the grating vector perpendicular to the plane of the surface.

10 Thus, as shown schematically in **FIG. 7a**, grating **130** includes periodic planes of polymer channels **130a** and PDLC channels **130b** which run parallel to the front surface **134**. The grating spacing associated with these periodic planes remains relatively constant throughout the full thickness of the sample from the air/film to the film/substrate interface.

15 Although interference is used to prepare both transmission and reflection gratings, the morphology of the reflection grating differs significantly. In particular, it has been determined that, unlike transmission gratings with similar liquid crystal concentrations, very little coalescence of individual droplets was evident. Furthermore, the droplets that were present in the material were significantly smaller, having diameters between 50 and

20 100 nm. Furthermore, unlike transmission gratings where the liquid crystal-rich regions typically comprise less than 40% of the grating, the liquid crystal-rich component of a reflection grating is significantly larger. Due to the much smaller periodicity associated with reflection gratings, i.e., a narrower grating spacing (~0.2 microns), it is believed that the time difference between completion of curing in high intensity regions versus low

25 intensity regions is much smaller. Thus, gelation occurs more quickly and droplet growth is minimized. It is also believed that the fast polymerization, as evidenced by small droplet diameters, traps a significant percentage of the liquid crystal in the matrix during gelation and precludes any substantial growth of large droplets or diffusion of small droplets into larger domains.

30 Analysis of the reflection notch in the absorbance spectrum supports the conclusion that a periodic refractive index modulation is disposed through the thickness of the film. For example, given a PDLC materials formed with a 488 nm line of an argon

ion laser, a resulting reflection notch may have a reflection wavelength at approximately 472 nm for normal incidence and a relatively narrow bandwidth. This small difference between the writing wavelength and the reflection wavelength (approximately 3%) indicates that shrinkage of the film is not a significant problem under these exemplary

5   conditions. Further, one skilled in the art recognizes that multiple write/reflect conditions are easily obtainable according to desired specifications and manipulations and adjustments to the recording geometry may also account for shrinkage, thus minimizing any resulting negative effects. Moreover, it has been found that the performance of such gratings is stable over periods of many months.
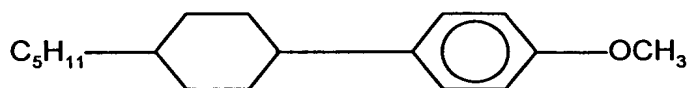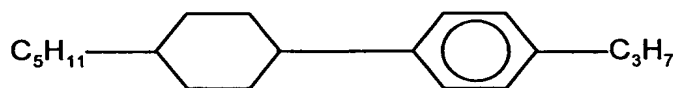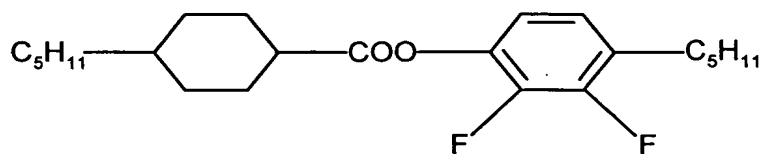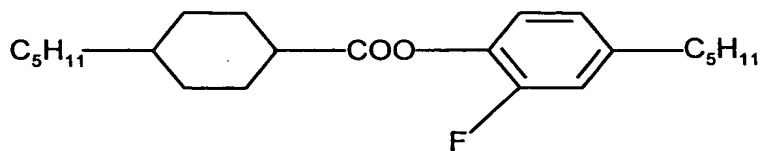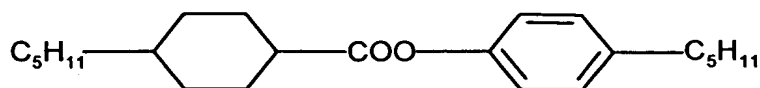
10   In addition to the materials utilized in a preferred embodiment described above, it is believed that suitable PDLC materials could be prepared utilizing monomers such as triethyleneglycol diacrylate, trimethylolpropane triacrylate, pentaerythritol triacrylate, pentaerythritol tetraacrylate, pentaerythritol pentaacrylate, and the like. Similarly, other coinitiators such as triethylamine, triethanolamine, N,N-dimethyl-2,6-diisopropylaniline,

15   and the like could be used instead of N-phenylglycine. Where it is desirable to use the 458 nm, 476 nm, 488 nm or 514 nm lines of an argon ion laser, the photoinitiator dyes rose bengal sodium salt, eosin, eosin sodium salt, fluorescein sodium salt and the like will give favorable results. Where the 633 nm line is utilized, methylene blue will find ready application. Finally, it is believed that other liquid crystals, such as 4'-pentyl-4-

20   cyanobiphenyl or 4'-heptyl-4-cyanobiphenyl, can be utilized in accordance with the invention.

    Referring again to **FIG. 7a**, there is shown an elevational view of a reflection grating **130** in accordance with the invention having periodic planes of polymer channels **130a** and PDLC channels **130b** disposed parallel to the front surface **134** of the grating

25   **130**. The symmetry axis **136** of the liquid crystal domains is formed in a direction perpendicular to the periodic channels **130a** and **130b** of the grating **130** and perpendicular to the front surface **134** of the grating **130**. Thus, when an electric field E is applied, as shown in **FIG. 7b**, the symmetry axis **136** is already in a low energy state in alignment with the field E and will not reorient. Thus, reflection gratings formed in

30   accordance with the procedure described above will not normally be switchable.
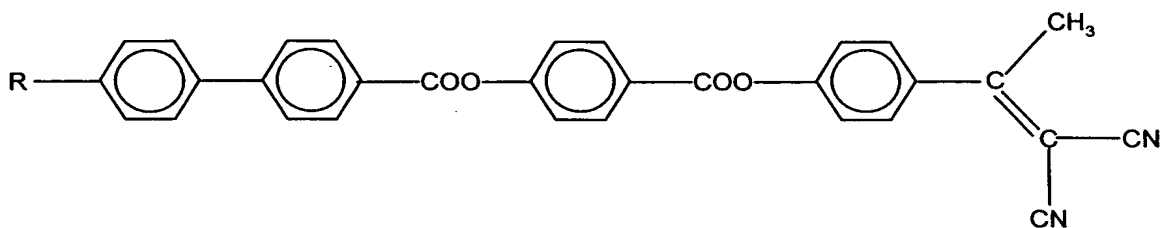
    In general, a reflection grating tends to reflect a narrow wavelength band, such that the grating can be used as a reflection filter. In a preferred embodiment, however,

17

the reflection grating is formed so that it will be switchable. In accordance with the present invention, switchable reflection gratings can be made utilizing negative dielectric anisotropy liquid crystals (or liquid crystals with a low cross-over frequency), an applied magnetic field, an applied shear stress field, or slanted gratings.
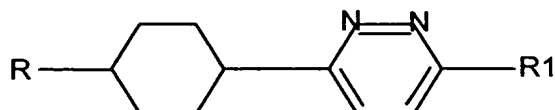
5   It is known that liquid crystals having a negative dielectric anisotropy ($\Delta\in$) will rotate in a direction perpendicular to an applied field. As shown in **FIG. 8a**, the symmetry axis **136** of the liquid crystal domains formed with a liquid crystal having a negative $\Delta\in$ will also be disposed in a direction perpendicular to the periodic channels **130a** and **130b** of the grating **130** and to the front surface **134** of the grating. However,

10   when an electric field E is applied across such gratings, as shown in **FIG. 8b**, the symmetry axis of the negative $\Delta\in$ liquid crystal will distort and reorient in a direction perpendicular to the field E, which is perpendicular to the film and the periodic planes of the grating. As a result, the reflection grating can be switched between a state where it is reflective and a state where it is transmissive. The following negative $\Delta\in$ liquid crystal

15   and others are expected to find ready application in the methods and devices of the present invention:

C_5H_{11}—⬡—COO—⬡—C_5H_{11}

C_5H_{11}—⬡—COO—⬡—C_5H_{11}
F

C_5H_{11}—⬡—COO—⬡—C_5H_{11}
F   F

C_5H_{11}—⬡—⬡—C_3H_7

C_5H_{11}—⬡—⬡—OCH_3

Liquid crystals can be found in nature (or synthesized) with either positive or negative $\Delta\epsilon$. Thus, in more detailed aspects of the invention, it is possible to use a liquid

5   crystal which has a positive $\Delta\epsilon$ at low frequencies, but becomes negative at high frequencies. The frequency (of the applied voltage) at which $\Delta\epsilon$ changes sign is called the cross-over frequency. The cross-over frequency will vary with liquid crystal composition, and typical values range from 1-10 kHz. Thus, by operating at the proper frequency, the reflection grating may be switched. In accordance with the invention, it is

10   expected that low cross-over frequency materials can be prepared from a combination of positive and negative dielectric anisotropy liquid crystal. A suitable positive dielectric liquid crystal for use in such a combination contains four ring esters as shown below:

R—⬡—⬡—COO—⬡—COO—⬡—C—CH₃
                                    ‖
                                    C—CN
                                    |
                                    CN

19

A strongly negative dielectric liquid crystal suitable for use in such a combination is made up of pyridazines as shown below:

5

$$R \underline{\hspace{1cm}} \left\langle \text{cyclohexyl} \right\rangle \underline{\hspace{1cm}} \left\langle \text{pyridazine} \right\rangle \underline{\hspace{1cm}} R1$$

Both liquid crystal materials are available from LaRoche & Co., Switzerland. By varying the proportion of the positive and negative liquid crystals in the combination, crossover frequencies from 1.4-2.3 kHz are obtained at room temperature. Another combination

10   suitable for use in the present embodiment is a combination of the following: p-pentylphenyl-2-chloro-4-(p-pentylbenzoyloxy) benzoate and 4-(p-pentylbenzoyloxy) benzoate and p-heptylphenyl-2-chloro-4-(p-octylbenzoyloxy) benzoate. These materials are available from Kodak® Company.

Now that the unique and advantageous optical and electrical qualities of the

15   PDLC material used herein have been set forth, the technique for reproducing holograms within this type of PDLC material will be described.

Referring once again to **FIG. 3** a system **30** for reproducing a switchable transmission hologram from a master hologram **35** is shown. For recording a transmission hologram, the master hologram **35** is mounted in the path of an incident

20   beam **33** at the Bragg angle. A PDLC blank **37** is optically contacted to the master hologram **35** at the same angle to form a master/blank assembly. Finally, an absorption filter **30** (e.g., neutral density) may optionally be placed behind the PDLC blank **37** in order to absorb extraneous radiation and avoid spurious reflections which may lead to the formation of unwanted interferograms within the PDLC blank **37**. The master/blank

25   assembly of master hologram **35**, PDLC blank **37**, and, optionally, absorption filter **30** is then illuminated using a single coherent incident beam **33** from radiation source **31**.

Utilizing the hologram duplication system of **FIG. 3**, the radiation source **31** emits a coherent radiation beam **33** (e.g., laser) that is directed towards a first surface of the master hologram **35**. Within master hologram **35**, part of incident beam **33** is

30   diffracted by the holographic grating **56**, forming diffracted beam **34**, and part of the

incident beam **33** is transmitted undiffracted, forming transmitted beam **36**. Both diffracted beam **34** and transmitted beam **36** pass through the second surface of the master hologram **35** and into the optically contacted first surface of the PDLC blank **37**. Within the PDLC blank **37**, the transmitted beam **36** and the diffracted beam **34** interfere,

5 forming a replica of holographic grating **56** therein.

Given a master hologram diffraction efficiency of 50%, wherein 50% of the incident beam power is diffracted as diffracted beam **34** and 50% of the incident beam power is transmitted as transmitted beam **36**, a 1:1 beam ratio will result. While 50% is often an ideal diffraction efficiency in the master for optimal hologram reproduction,

10 varying diffraction efficiencies will still result in a replica hologram.

Referring to **FIG. 4**, a system **40** for reproducing reflection holograms according to an embodiment of the present invention is shown. While similar to the transmission reproduction system **30** of **FIG. 3**, the reflection reproduction system **40** requires that PDLC blank **37** be located before the master hologram **35** within the optical path,

15 followed by an absorption filter **39**. As in **FIG. 3**, the PDLC blank **37**, master hologram **35** and filter **39** configuration is oriented at the Bragg angle with respect to the coherent incident beam **33** from radiation source **31**.

Utilizing the hologram duplication system of **FIG. 4**, the radiation source **31** emits a coherent radiation beam **33** (e.g., laser) that is directed towards a first surface of

20 the PDLC blank **37**. The incident beam **33** is transmitted through the PDLC blank **37** as transmitted beam **36**, passing through the second surface thereof and enters the first surface of the master hologram **35** which is optically contacted to the second surface of the PDLC blank **37**. Within the master hologram **35**, the incident beam **33** is diffracted by the holographic grating **56** located therein, creating diffracted beam **34**. Transmitted

25 beam **36** and diffracted beam **34** interfere within the PDLC blank **37** forming a replica of holographic grating **56** therein.

In the case of a reflection hologram, given a master hologram with a diffraction efficiency of 100%, wherein 100% of incident beam **33** is diffracted as beam **34** and the amount of incident beam **33** that is transmitted **36** is negligible, a 1:1 beam ratio will

30 result. However, a master hologram with a lower diffraction efficiency will still result in a replica hologram.

21

In the representative embodiments described above, the master hologram is not limited to a PDLC hologram. The master hologram may be, but is not limited to, a computer generated hologram, any of a variety of emulsion-type holograms, a photopolymer hologram, a photochromic hologram, a polymer dispersed liquid crystal
5   hologram, silver halide photographic emulsion hologram, dichromated gelatin hologram, photoresist hologram, photothermoplastic hologram, photorefractive crystal hologram, multiplexed hologram, white light hologram, rainbow hologram, thin holograms, in-line hologram, off-axis hologram, fourier hologram, fraunhofer hologram, diffractive optical element (DOE), holographic optical element (HOE), evanescent-wave hologram, image
10   hologram, amplitude hologram, phase hologram, volume hologram, surface hologram, transmission hologram, reflection hologram, or silver-halide sensitized gelatin hologram. Further, in order to fully take advantage of the switching characteristics inherent in the liquid crystal component of the PDLC material, electrodes may be attached to ITO glass slides (as described in **FIG. 6**) of either one or the other or both the master hologram **35**
15   and the PDLC blank **37**. By controlling the orientation of the liquid crystal layer of either the master hologram **35** or the PDLC blank **37** during the duplication process, the replica holograms may be formed so as to diffract either with the application of a specified voltage or in the absence of the application of a specified voltage, in order to meet design and system specifications.
20   While the aforementioned embodiments do not require a switchable holographic-PDLC ("H-PDLC") master, there are situations where it is advantageous to utilize a switchable H-PDLC master in the hologram replication process. In the following embodiments, the blanks are not restricted to the BDLC material described herein. One skilled in the art recognizes the alternative materials which may be used for the replica in
25   the proceeding embodiments of the present invention.
      In an embodiment of the present invention wherein an H-PDLC switchable master is advantageously utilized, the blank is exposed prior to recording in order to improve uniformity of the hologram and for aesthetic reasons. Pre-recording in this context means prior to exposure of the H-PDLC master. One skilled in the art will recognize when such
30   pre-recording irradiation is necessary based on the composition of the blank. For example, the materials discussed in K.T. Weitzel et al., "Hologram recording in DuPont photopolymer films by use of pulse exposure," Opt. Lett. 22, 1899 (1997) and V.N.

Mikhailov et al., "Pulse Hologram Recording in DuPont's Photopolymer Films," Proc. SPIE 3011, 200 (1997) both of which are incorporated by reference herein, benefit from pre-recording irradiation.

Since the method of reproduction in the embodiments of the present invention is

5 contact reproduction, the master and the blank are in close physical and optical proximity. If the master hologram is not capable of being switched OFF, any exposure radiation through the master hologram, will necessarily cause a pattern to be created within the blank. But, in the case where the master hologram is an H-PDLC master, the holographic nature of the master may actually be turned OFF and ON under electrical

10 control, such that in the OFF state, the H-PDLC master resembles a piece of transparent glass as shown in **FIG. 9a**. In **FIG. 9a**, the H-PDLC master reflection hologram **35** is turned OFF, such that the liquid crystals do not orient so as to form a holographic grating within the H-PDLC master. Consequently, a pre-recording beam **5** passes through the PDLC blank **37** and the H-PDLC master **35** without being reflected back through the

15 PDLC blank and forming an interference pattern therein. In the case of a transmission H-PDLC master, as shown in **FIG. 9d** the order of the PDLC blank **37** and the H-PDLC master **35** is reversed, such that the pre-recording beam **5** first passes through the master **35** which is OFF and then passes through the blank **37**, without forming any interference pattern with in the blank **37**. Pre-recording beam **5** may be the same beam as recording

20 incident beam **33** or it may be an auxiliary beam.

Similar to the pre-recording embodiment described above, one skilled in the art recognizes that post-recording irradiation may also be advantageous for certain contact replication scenarios. Post-recording exposure is useful with certain recording photopolymer materials (see e.g., Chemistry of Materials) for eliminating unconverted

25 monomers and bleaching unconsumed photosensitive dye. For example, it may be necessary to further expose the replicated hologram in order to permanently set the recording therein. In **FIG. 9b**, a reflection H-PDLC master **35** is ON when incoming beam **33** is incident thereon and is reflected as beam **34** so as to interfere within the blank **37** with incident beam **33**, forming an interference region therein. In a situation where

30 post-recording irradiation of the replication is necessary, the master hologram **35** is turned OFF and a post-recording beam **6** is incident upon what is now the replica of the master but, for simplicity, what we will continue to refer to as the blank **37** but, is not

reflected back through by the master **35** because the grating therein is not ON (see **FIG. 9c**).

As with the pre-recording situation, post-recording may also take place when replicating a transmission hologram. Referring to **FIG. 9e** replication of a transmission master **35** occurs when an incident beam **33** passes through an ON master **35**, wherein part of the incident beam is deflected by the hologram pattern formed therein resulting in diffracted beam **34**. Beams **33** and **34** interfere within the blank **37** to form a replica of the hologram pattern of the master **35**. After this replication step has occurred, it is preferable in some situations to irradiate the now replica (used to be blank) **37** with a post-recording beam **6** as shown in **FIG. 9f**. Consequently, after the blank **37** has been exposed with the hologram of the master **35**, the master **35** is turned OFF and a post-recording beam **6** is direct through the master **35** and into the replica **37**, without re-forming the hologram of the master **35** but merely allowing the beam to pass unmodulated, through the master **35**. Post-recording beam **6** may be the same beam as recording incident beam **33** or it may be an auxiliary beam.

Both the pre-recording and the post-recording embodiments utilizing the H-PDLC master improve the efficiency of contact printing. Without the benefit of the switchable master, there are significant physical changes to the printing component which must occur before and after the actual exposure. First, the blank would have to be pre-exposed without being in optical contact with the master, next for the recording step, the master would have to be optically contacted thereto, and finally, for post-recording, the master would have to be removed from the blank (now replica) prior to irradiation of the blank with the post-recording beam. These multiple configurations for pre-recording exposure, recording exposure, and post-recording exposure add significant time to the contact printing process and reduce efficiency. Using the H-PDLC master, allows for a single configuration during the performance of all three exposure steps.

In another embodiment of the present invention, using a switchable H-PDLC master allows for substantial control of diffraction efficiency. When contact printing planar transmission gratings, the incident beam is split into two beams, a transmitted beam and a diffracted beam. The optimum beam balance between the transmitted and diffracted beams is often 1:1 since the beams are overlapping to form the replica

24

holographic transmission grating within the blank. With a static master hologram, the diffraction efficiency may not be selectively turned OFF and ON and it is not variable. Consequently, given a static hologram which does not meet the 1:1 requirement, there is a limitation in the quality of the replica due to the non-optimal diffraction efficiency. In an embodiment wherein the master is a switchable H-PDLC, the diffraction efficiency is voltage controlled. Consequently, the optimum efficiency can in effect be tuned in. This ability to change or tune the diffraction efficiency in order to achieve the optimal 1:1 power ratio is extremely useful where the hologram to be replicated is complex. For example, where the master hologram is a lens or some other complicated fringe pattern, the diffraction efficiency may be manipulated in order to find the beam ratio, be it 1:1 or otherwise, that produces the replica with highest fidelity.

Referring to **FIG(s). 10a** and **10b**, incident recording beam **33** is split into transmitted beam **36** and diffracted beam **34** by only partially switching the master H-PDLC hologram **35**. The ability to partially switch the master is analogized to an analog signal as opposed to a digital signal. Instead of choosing from two states, all ON or all OFF, a partially switchable H-PDLC master allows for a range of diffraction efficiencies. For example, as the applied voltage varies through a range, the diffraction efficiency of the master also varies through a range. In **FIG. 10a**, a reflective master is contact printed when the incident beam **33** and the diffracted beam **34** interfere within the blank **37**. Due to the use of the switchable H-PDLC master, the power of the diffracted beam may be varied with voltage as desired. Similarly, in **FIG. 10b**, the transmitted beam **36** and the diffracted beam **34** interfere within the blank **37** and both the transmitted beam power and the diffracted beam power are capable of voltage control.

In another embodiment of the present invention, the switchable H-PDLC master is utilized in order to create replica holograms with tailored diffraction efficiency through decreased fringe contrast. In many material systems, holographic exposure with low fringe contrast will result in a replica with less than optimum diffraction efficiency. By adjusting the diffraction efficiency of the switchable master, the writing beams become imbalanced (or the optimum balance for the system is altered) and thus a decreased replica diffraction efficiency results. There are situations where a power ratio other than 1:1 is desired during the replication process (see e.g., D.J. Lougnot et al., "Photopolymers for Holographic Recording: IV. New Self-processing Formulations Based on β-hydroxy

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ethyloxazolidone acrylate," Pure Appl. Opt. 2, 383 (1993) incorporated herein by reference). In a particular embodiment benefiting from this method, a single switchable H-PDLC master is able to produce multiple replicated static holograms with identical prescriptions but with various diffraction efficiencies. Without the partial switching

5   capability of the H-PDLC master, multiple static masters with varying photopolymer recipes must be used to create this result. This method and system are cumbersome and inefficient. Additionally, decreased diffraction efficiency can also be achieved by decreasing the overall incident power. However, the total incident power in that case would not be maintained so as to preserve reaction rates within the blank. This

10   embodiment of the present invention preserves the total power incident on the blank to preserve reaction rates.

Further embodiments of the present invention comprise a stack of switchable H-PDLC masters. As with non-holographic lens configurations forming an optical train . (e.g., camera lenses), two or more stacked holographic lenses, either reflection or

15   transmission, comprising an optical train also require precise predetermined alignment of their optical centers or registration, as it is referred to by those skilled in the art. An embodiment of the present invention utilizes two or more switchable H-PDLC masters to consecutively record two or more independent holographic lenses. Referring to **FIG. 11(a)**, when contact printing multiple reflection masters in accordance with a preferred

20   embodiment of the present invention, the first replica lens **37a** is recorded with the first master **35a** switched ON and the second master **35b** switched OFF (not shown). Next, the second replica lens **37b** is recorded with the second master **35b** switched ON and the first master **35a** switched OFF. Similarly, referring to **FIG. 11(b)**, when contact printing multiple transmission masters in accordance with a preferred embodiment of the present

25   invention, the first replica lens **37a** is recorded with the first master **35a** switched ON and the second master **35b** switched OFF (not shown). Next, the second replica lens **37b** is recorded with the second master **35b** switched ON and the first master **35a** switched OFF. By sequentially switching the masters, interference and cross talk are eliminated during replication. One skilled in the art will appreciate that the masters must be

30   designed, recorded and registered appropriately, considering parameters such as the distance between corresponding master/replica pairs, spectral properties, etc., in order to yield the proper optical properties and registration in the replica stack.

26

Another preferred embodiment of the present invention is a system and method for mass producing a Red-Green-Blue (RGB) holographic lens stack according to the principles illustrated with regard to **FIG(s) 11(a)-(b)**. Holographic lenses have unique applications in the art of personal displays in that their optical properties cannot be

5 reproduced with conventional refractive optics. In such personal displays a color image is produced by rapidly sequencing independent red, green, and blue images. To avoid color cross talk and interference, switchable H-PDLC lenses are employed, allowing only the appropriate color hologram(s) to be ON during the RGB sequence. Precise registration of the RGB H-PDLC stack is required so that the three monochrome images overlap.

10 Current manufacturing procedures require each monochrome hologram to be independently recorded in independent complex optical rigs that require painstaking alignment. This alignment must be such that each hologram is placed in a precise location in a substrate blank of specific dimensions. Each monochrome hologram is recorded using a laser of a similar wavelength. If successful, the three monochrome holograms

15 will register when they are physically stacked and aligned. Registration can be compromised if any one recording rigs become misaligned or the blank substrate dimensions is out of specification. This manufacturing technique is subject to serious downtime and costly maintenance. The following method and system of an embodiment of the present invention eliminate the complex alignment in the mass production step and

20 thus reduce the risk of production delays.

Initially, a master set of holograms is designed, recorded, and registered into a master switchable holographic stack, taking into account the required replica optical design, registration, blank substrate dimensions, etc. A fixture is provided to hold the master and replica stacks in optical contact. Next, stable, optically clean and uniform

25 laser beams of three different wavelengths (e.g., red, green, blue) are provided to illuminate the master/replica assembly. The angle of incidence of each of the RGB beams onto the master/replica assembly is set according to the master designs.

Following the sequence set forth in TABLE 1 and referencing **FIG(s). 12(a)-(b)**, the recording of the master switchable holographic stack is described. In **FIG. 12(a)**, a

30 stack of reflective RGB H-PDLC masters is contact printed. First, if necessary based on the material comprising the blue blank **37a**, a pre-recording irradiation is performed while all masters and blanks are OFF, utilizing the blue laser beam or an appropriate

auxiliary beam. Next, while recording the blue H-PDLC master **35a** onto the designated blue blank **37a**, all masters and blanks excepting the blue H-PDLC master **35a** are switched OFF, leaving only the blue H-PDLC master **35a** ON and irradiated by the blue laser. Following the recording step, if post-recording exposure is necessary, again, all

5   masters, remaining red and green blanks and the blue replica are switched OFF while the blue laser or an auxiliary beam irradiates the blue replica.

After the blue blank (now replica) **37a** has been recorded, the green blank **37b**, is pre-exposed (if necessary) utilizing the green laser or an auxiliary beam, while all masters, the red and green blanks, and the blue replica are switched OFF. As is

10   specifically shown in **FIG. 12(a)**, while recording the green H-PDLC master **35b** utilizing green incident beam **33b**, the blue and red masters **35a, 35c**, the red and green blanks **37b, 37c**, and the blue replica **37a**, remain switched OFF, while the green master **35b** is switched ON. Green incident beam **33b** and diffracted beam **34b** interfere within the green blank **37b** to form the replica. Following the recording step, if post-

15   recording exposure is necessary, all masters, the red blank, and the blue and green replicas are switched OFF while the green replica is irradiated with the green laser or an auxiliary beam.

Finally, after the blue blank (now replica) **37a** and green blank (now replica) **37b** have been recorded, the red blank **37c**, is pre-exposed (if necessary) utilizing the red laser

20   or an auxiliary beam, while all masters, the red blank, and the blue and green replicas are switched OFF. While recording the red H-PDLC master **35c** utilizing the red laser, the blue and green masters, the red blank, and the blue and green replicas, remain switched OFF, while the red master **35c** is switched ON. Fóllowing the recording step, if post-recording exposure is necessary, all masters and the blue, green, and red replicas are

25   switched OFF while the red replica is irradiated with the red laser or an auxiliary beam.

When recording a stack of transmission RGB H-PDLC masters, the sequence described above is applicable. The only difference lies in the interacting beams used to form the interference pattern within the appropriate blank during the recording step. For

30   example, referring to **FIG. 12(b)**, while recording the green H-PDLC master **35b** utilizing green incident beam **33b**, the blue and red masters **35a, 35c**, the red and green blanks **37b, 37c**, and the blue replica **37a**, remain switched OFF, while the green master

35b is switched ON. Unlike in the reflection recording step, the diffracted beam **34b** and the transmitted beam **36b** interfere within the green blank **37b** to form the replica.

Sample Switching Sequence in an RGB Stack Produced by Contact Holography						
	Red Blank/ Replica	Green Blank/ Replica	Blue Blank/ Replica	Red Master	Green Master	Blue Master
Pre-ex Blue	N/A	N/A	N/A	Off	Off	Off
Expose Blue	N/A	N/A	N/A	Off	Off	**ON**
Post-ex Blue	N/A	N/A	N/A	Off	Off	Off
Pre-ex Green	N/A	N/A	Off	Off	Off	Off
Expose Green	N/A	N/A	Off	Off	**ON**	Off
Post-ex Green	N/A	N/A	Off	Off	Off	Off
Pre-ex Red	N/A	Off	Off	Off	Off	Off
Expose Red	N/A	Off	Off	**ON**	Off	Off
Post-ex Red	N/A	Off	Off	Off	Off	Off

5

TABLE 1

In constructing the system described in the previous embodiment for contact printing of multiple stacked holograms of varying colors, considerations must be given to

10 the photo-sensitive materials used in the replica blanks to ensure that they do not spectrally overlap. Further, one skilled in the art recognizes that the aforementioned embodiments are merely representative of the multiple useful configurations and methods which are possible when a switchable PDLC master and/or blank are incorporated therein.

15 The replica PDLC holograms resulting from the systems and methods described above, because of the switching properties of the liquid crystal component of the PDLC material, may be switched accordingly from a diffractive to a transmissive state. Consequently, the duplication method described above allows for increased efficiency and reproducibility of switchable holographic elements. These switchable holographic

20 elements find use in all areas of technology utilizing optical switches including the telecommunications and imaging technologies.

Given the aforementioned examples of hologram reproduction using a single beam approach with a PDLC blank, one skilled in the art is readily aware of the importance of this improved method when considering the manufacturing process of, for

25 example, holographic lenses which use complex optical geometries. The set-up time is

29

considerably reduced and the overall reproducibility from one hologram to another is significantly increased.

      Further, one skilled in the art recognizes that the embodiments illustrated herein are merely exemplary and that the inventive concepts may be practiced in any number of

5   alternate embodiments while remaining within the scope of the present invention.